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LIFE CYCLE MANAGEMENT

Life cycle assessment comparison of substrates for the bioremediation of pentachloroaniline under acidogenic/methanogenic conditions

Jinglan Hong · Xiangzhi Li

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Abstract
Purpose In general, pentachloroaniline (PCA) biodechlorination is specific to the conditions of a system; such conditions include the type and concentration of electron donors and oxidizing agents as well as nutrient availability, pH, and temperature. In the bioremediation of contaminated sediments and soil, most researchers have focused on the ability of various electron donors to remove target compounds. However, the amended electron donors and the byproduct of the anoxic/anaerobic systems may cause more environmental impact. Therefore, methods for consistently evaluating the environmental effects of such electron donors and byproducts are highly needed. Accordingly, life cycle assessment (LCA) was carried out to estimate the environmental effect of PCA biodechlorination under acidogenic/methanogenic conditions through laboratory-scale experiments. Four scenarios, intended to assess the influence of electron donors on the environment and develop laboratory experimental research, were compared. In these scenarios, four compounds were used: acetate, lactate, methanol, and glucose + methanol.
Materials and methods The LCA was carried out using IMPACT2002+ to estimate the environmental impact of PCA biodechlorination under acidogenic/methanogenic conditions. To add credibility to the study, sensitivity analysis was also conducted.
Results and discussion In all scenarios, the technologies significantly contributed to respiratory inorganics, global warming, as well as increased the adverse impact of nonrenewable energy on the environment. Specifically, the emissions from the electron donor production processes played an important role in the scenarios. PCA dechlorination and methanogenic processes substantially contributed to the aquatic/terrestrial ecotoxicity and global warming, respectively.

Optimizing the concentration of amended electron donors and increasing the population size of dechlorinating microorganisms are highly important in reducing the environmental burden by PCA bioremediation.
Conclusions Results showed that the methanol scenario was the most suitable option determined in this research. In addition, results indicate amended electron donors can cause fewer environmental impacts in carcinogens and noncarcinogens categories. By contrast, the amended electron donors can significantly increase environmental impacts in respiratory inorganics, global warming, and nonrenewable energy categories. Increasing the population size of dechlorinating microorganisms and optimizing the concentration of amended electron donors are highly recommended to reduce adverse environmental impacts.

Keywords Bioremediation · Electron donor · Environmental impact · Life cycle assessment · Pentachloroaniline

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J. Hong (✉)
Shandong Provincial Key Laboratory of Water Pollution Control and Resource Reuse, School of Environmental Science and Engineering, Shandong University,
Jinan 250100, Shandong, People's Republic of China
e-mail: hongjing@sdu.edu.cn

J. Hong
Shandong University Climate Change and Health Center, Public Health School, Shandong University,
Jinan 250100, Shandong, People's Republic of China

X. Li
Shandong University School of Medicine,
Jinan 250012 Shandong, People's Republic of China

1 Introduction

Pentachloroaniline (PCA) is an organochlorine compound that is mainly produced as a result of the biotransformation of pentachloronitrobenzene (PCNB), which has been classified as a possible cancer-causing substance by the US Environmental Protection Agency (US EPA 2003). PCNB is widely used as a fungicide and is employed for the prevention of slime formation in industrial water systems. Under reductive biotic and abiotic conditions, PCA is the first product of PCNB. However, PCA is not easily dechlorinated, especially in environments where PCA dechlorination does not take place (Tas and Pavlostathis 2010). This compound is widespread in every environmental compartment (e.g., soil, water, and air; Sutton et al. 2004). The persistence of these polychlorinated compounds in the environment, along with their toxicity and carcinogenicity, poses a threat to the health and safety of humans and wildlife (Tomy et al. 1998).

Compared with traditional remediation methods (e.g., landfill, solidification or stabilization, chemical oxidation, and soil vapor extraction), bioremediation has attracted considerable attention for the following reasons: (1) it completely eliminates target chemicals; (2) it is cost-effective; (3) it causes no contaminant transfer from one medium to another; and (4) it consumes little energy. Hence, PCA bioremediation was considered in the present study. The common technologies for in situ bioremediation include the addition of nutrients (nitrogen and phosphorus), carbon sources, and specific bacteria as well as the modification of temperature, PH, moisture, etc. Biodechlorination is specific to the conditions of a system; such conditions include the type and concentration of electron donors and acceptors as well as nutrient availability, pH, and temperature (Tas and Pavlostathis 2007, 2008). For the bioremediation of contaminated sediments and soil, most researchers have focused on the ability of various electron donors to remove target compounds (Middeldorp et al. 2005; Thomas et al. 2008). However, the amended electron donor and the byproduct of the anoxic/anaerobic systems may cause more environmental impacts. Thus, methods for consistently evaluating their environmental impact are highly needed.

Life cycle assessment (LCA) is used to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy, materials used, and waste released into the environment. It is also applied to assess the impact of the energy and materials used and released into the environment as well as to identify and evaluate opportunities for environmental improvement (Curran 2004). The environmental effect of remediation has been extensively studied via the LCA method. Recent studies (Lemming et al. 2010a; Morais and Delerue-Matos 2010; Higgins and Olson 2009) mainly focused on the ex situ remediation of heavy metals, PAHs, hydrocarbons, and chlorinated solvents. Lemming et al. (2010b) extended the scope of these studies by comprehensively analyzing the environmental impact of three alternative chlorethene-contaminated treatment scenarios, namely, in situ bioremediation, in situ thermal desorption, and off-site treatment. Their results showed that in situ bioremediation poses the best environmental benefit because of the lower energy required in this technology. To date, however, no LCA studies have focused on the environmental impact of PCA in in situ bioremediation. To evaluate the environmental impact of various electron donors for the bioremediation of contaminated sediments and soil and to develop laboratory experimental research, we carried out LCA to estimate the environmental impact of PCA biodechlorination under acidogenic/methanogenic conditions through laboratory-scale experiments.

2 Scope

2.1 Functional unit

The functional unit is dechlorination of 1 μM PCA in sludge. All emissions, energy consumption levels, and materials are based on this functional unit.

2.2 System boundaries

In general, electron donors for reductive dechlorination include various volatile fatty acids (VFAs), sugars, hydrogen, and polymeric compounds. For PCA dechlorination in this study, acetate, methanol, glucose + methanol, and lactate were the electron donors tested. Figure 1 presents the system boundary of this study. The production processes for experimental equipments, bottles, and ion water were excluded because they are common to all the scenarios. The processes included in the anaerobic and decholorination system are summarized as follows:

- production of methanol, glucose, lactate, and acetate;
- road transport of electron donor to the laboratory site (assuming a distance of 100 km); and
- emissions from acidogenic, methanogenic, and dechlorinating processes.

The life cycle inventory was used to compare the environmental impact of various electron donors on the basis of the results of the same boundaries. The impact of the scenarios is the sum of the impact generated from each process.

2.3 Life cycle impact assessment methodology

The life cycle impact assessment results were calculated at midpoint and damage levels using the IMPACT2002+

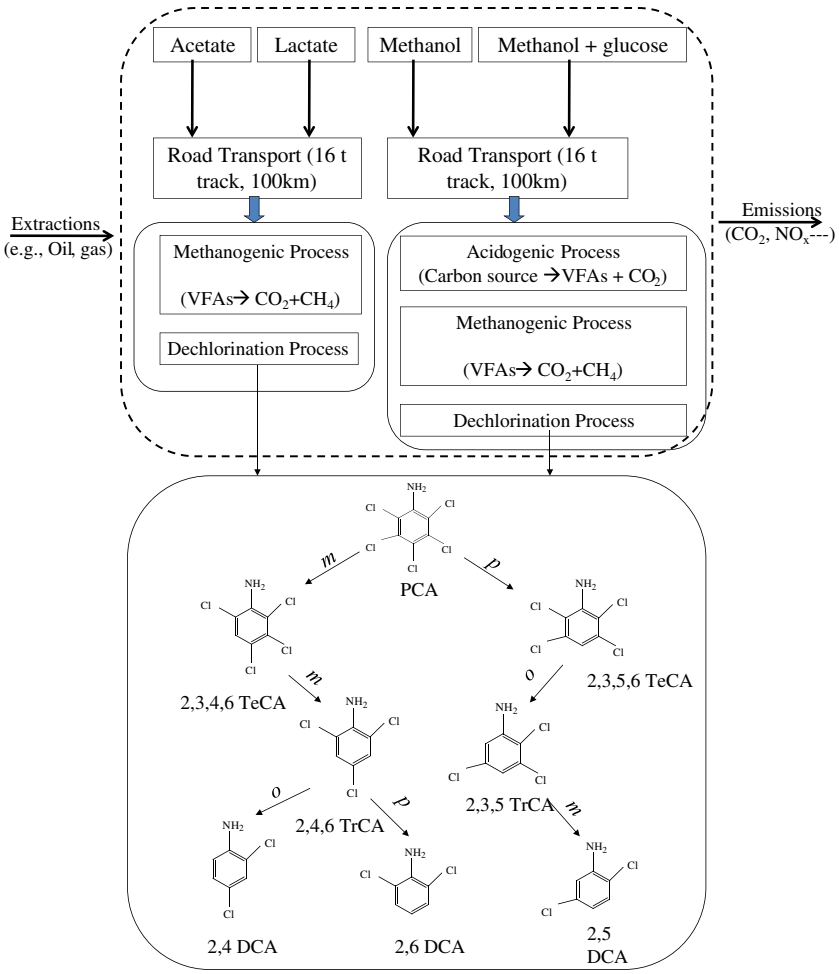

Fig. 1 Scenario flows and system boundaries. *o Ortho-*, *m meta-*, *p para-*

method (Jolliet et al. 2003). This method was chosen because the IMPACT2002+ model has PCNB, and its byproducts impact factor very well and consistently treats fate exposure in multimedia modeling. This method is a combination of results of the IMPACT2002 model for human health (Pennington et al. 2005), Eco-indicator 99 (Goedkoop and Spriensma 2000) and CML (Guinée et al. 2001). This approach defines 15 midpoint categories including carcinogens, noncarcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nutrification, land occupation, aquatic acidification, aquatic eutrophication, global warming, nonrenewable energy, and mineral extraction, all of which are connected to the inventory results. These midpoint categories except for the global warming are structured into three damage categories: human health, ecosystem quality, and resources depletion. Also, to analyze the respective share of each midpoint impact to the overall impact and to compare the midpoint impact to each other as well, normalization was applied in this study. The normalized factor of midpoint impact is determined by the ratio of the impact per unit of emission divided by the total impact generated from European emissions per person per year (Jolliet et al. 2003). In addition, the ReCiPe (midpoint E; Goedkoop et al. 2009; De Schryver et al. 2009) method was used to complement IMPACT2002+ and to check the robustness of the results obtained from the latter.

2.4 Inventory data sources

LCA was conducted in accordance with ISO 14040 standards. Information on acetate and methanol production, road transport, and relevant background data from the reference were used (Frischknecht et al. 2005). Table 1 shows the description of each scenario. Carbon dioxide (CO_2) emissions generated from methanogenic process in corn-based scenarios are omitted from the inventory because corn is considered a biogenic source. However, biogenic carbon released as methane is included. Data on emissions from acidogenic, methanogenic, and dechlorinating processes were obtained from batch experiments. The dechlorinating enrichment culture was developed from contaminated sedi-

Table 1 Description of the scenarios

Scenario	Process	Reference
Methanol + glucose	Methanol, at regional storage/CH U Glucose production from corn (data coming from Desmet Ballestra company environmental report) Corn, at farm/US U (without metal uptake)	Frischknecht et al. 2005; Desmet Ballestra 2010
Methanol	Methanol, at regional storage/CH U	Frischknecht et al. 2005
Lactate	Process "Polylactide, granulate, at plant/ GLO U" is modified as follows: (1) The metal uptake of process "Corn, at farm/US U" is deleted. (2) Energy consumption during polymer production stage is deleted.	Frischknecht et al. 2005; Vink et al. 2010
Acetate	Acetic acid, 98% in H_2O, at plant /RER U	Frischknecht et al. 2005

ment (Nalecz-Jawecki et al. 2003). The culture was fed weekly and maintained at 22°C. Glucose (333 mg/L), yeast extract (17 mg/L), and methanol (53 mg/L) were the carbon sources. The steady-state biomass concentration was 500± 20 mg/L (expressed as particulate organic carbon). Detailed information on culture development was reported elsewhere (Tas and Pavlostathis 2005). Batch assay was performed to investigate PCA bioreductive transformation. The assay was conducted in 160-mL serum bottles (liquid volume, 120 mL) sealed with Teflon-lined stoppers and aluminum crimps, and then flushed with helium gas for 15 min at 10 psi pressure before any liquid addition. Aliquots of diluted dechlorinating culture (at the end of the weekly feeding cycle) and media were transferred to the serum bottles. It is worth noting that the feed of PCA and carbon source for biomass was completed consumed at the end of the weekly feeding cycle. Thus, the feed of culture are excluded in the system boundary, as they were common to all the scenarios. All the serum bottles, except the seed blank, were amended with PCA at an initial concentration of 4.8 μM, which is not inhibitory to the effect on the activity of the dechlorinating enrichment culture (Tas 2006). Glucose (333 mg/L) plus methanol (1,581 mg/L), methanol (1,817 mg/L), acetate (2,513 mg/L), and lactate (2,527.3 mg/L) served as the carbon sources and electron donors, based on the soluble chemical oxygen demand (COD) mass balance from Eqs. 1 to 4, respectively. Here, it is noteworthy that VFAs (e.g., acetic acid, propionic acid, butyric acid) are intermediates in the production of methane. Accordingly, the COD processed as methane and VFAs was monitored throughout the incubation period in these sets as an indicator of methanogenic and acidogenic activity, respectively.

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \quad (1)$$

$$CH_3OH + 3/2O_2 \rightarrow CO_2 + 2H_2O \quad (2)$$

$$CH_3COO^- + H^+ + 2O_2 \rightarrow 2CO_2 + 2H_2O \quad (3)$$

$$CH_3CH(OH) \cdot COO^- + H^+ + 3O_2 \rightarrow 3CO_2 + 3H_2O \quad (4)$$

No more electron donor and PCA were amended during the incubation period. Higher initial electron donor concentrations were used in this research to eliminate any electron donor limitations. The fraction of electron equivalents diverted to dechlorination reactions relative to methanogenesis was very low. Only 0.008–0.014% of the electron equivalents are used for dechlorination (Tas et al. 2006). Triplicate serum bottles were prepared for each culture series. One serum bottle was used for headspace sampling and the other two were used for aqueous sampling. The culture series were incubated at 22°C in the dark and the bottles were manually shaken once a day. The initial pH in all the culture series was 7.6. Throughout the incubation period, the total gas volume produced, as well as its methane and CO_2 content, pH, VFAs, particulate organic carbon, and COD, were measured. Total gas produced was measured by acid brine (10% NaCl w/v, 2% H_2SO_4 v/v) displacement. Particulate organic carbon was determined using a Shimadzu TOC-5050A Total Organic Carbon Analyzer equipped with a Shimadzu SSM- 5000A Solid Sample Module and nondispersive infrared detector. COD and pH were measured following the procedures outlined in standard methods (American Public Health Association 1998). The gas composition, VFAs, and chlorinated compounds were determined by gas chromatography with thermal conductivity, flame ionization, and electron capture detection, respectively, as previously reported (Tas and Pavlostathis 2005). At the end of incubation, cumulative PCA-biodechlorinated products, VFAs, methane, and CO_2 emissions were used to compare the environmental impacts among the scenarios. The cumulative PCA-biodechlorinated products that were emitted to

soil were quantified in this study because of its very low solubility.

3 Results

3.1 Effect of electron donors on the reductive transformation of PCA

The effect of electron donors on the reductive transformation of PCA was investigated by batch assay. Although PCA transformation in the lactate- and acetate-amended cultures was slower than that in the methanol- and glucose + methanol-amended cultures, the PCA dechlorination pathway and cumulative gas (methane and CO_2) production were unaffected. In all the cultures, PCA was dechlorinated down to anilines, which are also relatively toxic (Tas 2006). About 161.6 mg/g COD cumulative methane and 84.1 mg/g COD cumulative CO_2 production were produced. VFAs and COD were completely consumed at the end of incubation. These results indicate that the electron donor was completely consumed and transferred to methane and CO_2. Similar results were observed by Tas (2006) who tested the dechlorinated electron donors of acetate, methanol, glucose + methanol, and hydrogen under acidogenic/methanogenic conditions. The PCA transformation rates in the cultures fed with glucose + methanol and methanol were significantly faster than those fed with acetate and hydrogen. The PCA biotransformation profile in the glucose + methanol-amended culture is shown in Fig. 2. The isomers of tetrachloroaniline (mainly 2,3,5,6-TeCA), trichloroaniline (mainly 2,3,5-TrCA and 2,4,6-TrCA), and dichloroaniline (mainly 2,4/2,5-DCA and 2,6-DCA) were formed gradually. Given the relatively high minimum detection limit of monochloroanilines (CAs) by GC/ECD, during the PCA biotransformation assay CAs, could not be quantified during the PCA biotransformation assay. However, references show that PCA can be biodechlorinated to CAs under acidogenic/methanogenic conditions (Tas and Pavlostathis 2005). Furthermore, studies show that the biodechlorinated product can be degraded further under aerobic conditions (Surovtseva et al. 1996). Conclusively, in the current work, the acidogenic/methanogenic enrichment culture reduced PCA to DCA isomers and converted the electron donor to methane and CO_2.

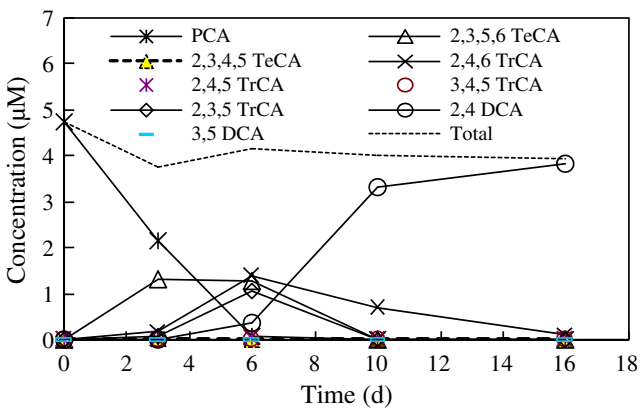

Fig. 2 PCA and its biotransformation products

3.2 LCA results

Figure 3 shows the normalized midpoint categories in each scenario. For all the scenarios, the impact on respiratory inorganics, global warming, and nonrenewable energy categories had an important contribution, whereas that of the rest of the categories was negligible except for the land occupation and terrestrial ecotoxicity categories. In the glucose + methanol and methanol scenarios, low potential impact generated from the abovementioned dominant categories was observed. The higher potential impact of the acetate and lactate scenarios is attributed primarily to the emissions generated from acetate and lactate production. Specifically, for the glucose + methanol scenario, the potential impacts on the respiratory inorganics and land occupation categories were slightly higher than that observed in the methanol scenario. The impact on the nonrenewable energy had a relatively low value. By contrast, the highest potential impact was observed in the lactate scenario in the abovementioned dominant categories, except for nonrenewable energy. Notably, the lactate scenario, which has a higher global warming and a lower nonrenewable energy potential than the acetate, is attributed primarily to the use of light fuel oil for corn drying.

To better elucidate the dominant pollutants in the abovementioned dominant categories, the contributions of the most significant substances to these midpoints are shown in Fig. 4. For all the scenarios, the substances contributing most to respiratory inorganics were sulfur dioxide, particulate, and nitrogen oxide emissions in air. Ammonia emission in the lactate and methanol + glucose scenarios represented dominant contributions to respiratory inorganics. These dominant substances were mainly generated electron donor production stage. Similarly, in the terrestrial ecotoxicity category, the emissions of aluminum, copper, and zinc generated from each electron donor production stage gave the highest contributions. In addition, accumulated DCAs emission from dechlorination stage imposed a significant effect on the terrestrial ecotoxicity score. In the global warming score, direct methane emission seen from methanogenic stage and CO_2 emission seen from electron donor and transport stages were dominant substances, whereas the use of coal, natural gas, crude oil, and uranium for electron donor production played an important role in nonrenewable energy. For land occupation, arable

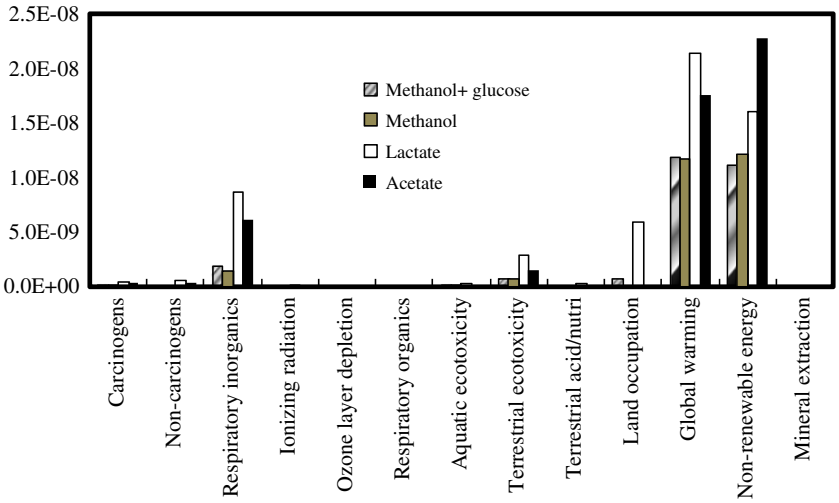

Fig. 3 Normalized midpoint scores for the full life cycle

occupation was the dominant contributor in the lactate and methanol + glucose scenarios.

Figure 5 shows the damage endpoint categories in each scenario, combining most midpoint categories except for global warming into damages to human health, ecosystems, and abiotic resources. For all damage categories, the methanol + glucose and methanol scenarios exhibited relatively low potential impact. The results observed in the damage level were consistent with those observed in the midpoint level. In the methanol scenario, a decrease was observed in the ecosystem quality and human health categories. The relatively high impact on the respiratory inorganic and land occupation categories is attributed to corn planting for glucose production. These results indicate that the methanol and methanol + glucose scenarios may be suitable for PCA biodechlorination.

4 Sensitivity analysis

4.1 Sensitivity to electron donor application

As previously mentioned, higher initial electron donor concentrations were used in this research. Only 0.008–0.014% of the electron equivalents diverted to dechlorination reactions (Tas et al. 2006). This result indicates that the electron donor application exceeds actual demand by two or three orders of magnitude. Table 2 shows the sensitivity

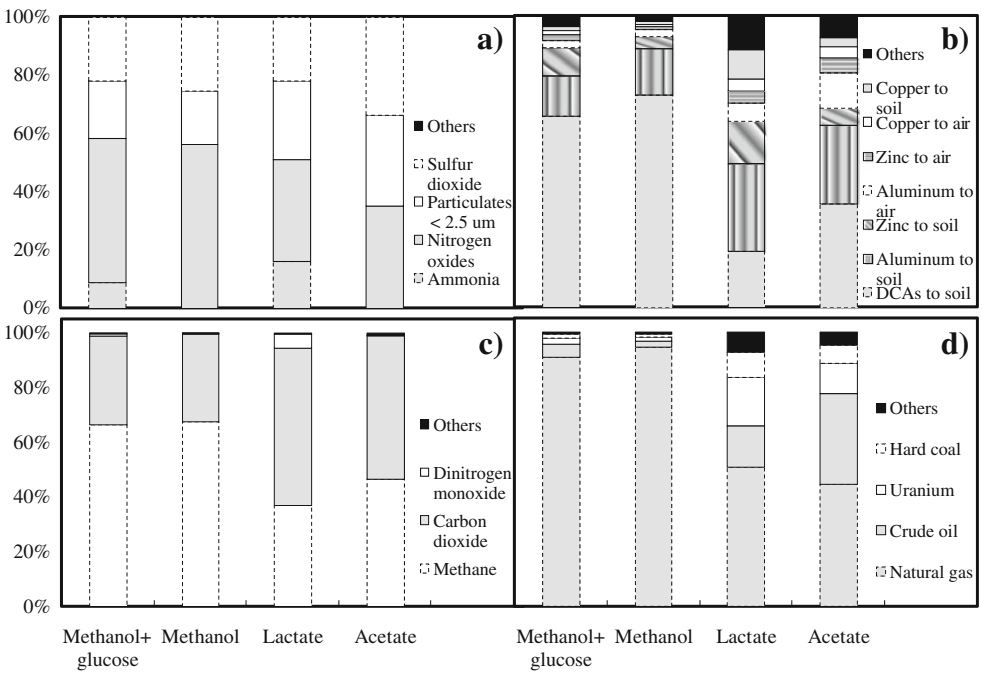

Fig. 4 Contribution of substances to the midpoint score for **a** respiratory inorganics, **b** terrestrial ecotoxicity, **c** global warming, **d** nonrenewable energy (IMPACT2002+)

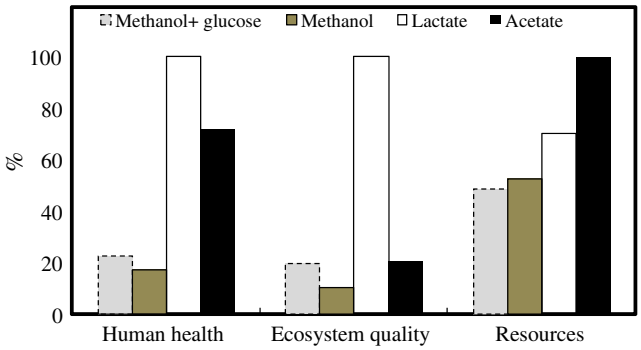

Fig. 5 Comparative endpoint assessment for the full life cycle, relative to the highest score among scenario

analysis of electron donor application in each scenario. The potential impact on each key midpoint category linearly decreased with decreasing electron donor application. For the acetate scenario, a 20% decrease in the electron donor application would decrease about 1.3×10^{-8} kg PM2.5 eq, 3.5×10^{-4} kg TEG soil, 9.2×10^{-8} m^2org.arable, 3.5×10^{-4} kg CO_2 eq, and 6.9×10^{-4} MJ primary on respiratory inorganics, terrestrial ecotoxicity, land occupation, global warming, and nonrenewable energy potential score, respectively. For the rest of the categories, a similar analogy could be made with the sensitivity results shown in Table 2.

4.2 Sensitivity to impact assessment method

To confirm and add credibility to this research, the ReCiPe method was used for comparison with the results of IMPACT2002+. The midpoint value of the ReCiPe method tended to be similar to the IMPACT2002+ analysis results in the climate change, ozone depletion, terrestrial acidification, and land occupation categories. The rest of the midpoint values were difficult to compare because the categories or label substances were significantly different. Figure 6 shows the midpoint assessment results in related categories of each scenario obtained using the ReCiPe and IMPACT2002+ methods. Similar to the IMPACT2002+ midpoint assessment results, the processes of electron donor production represented the dominant contribution to each score, whereas the impact observed in the acidogenic process was negligible. The methanogenic process also contributed significantly to the climate change score. However, no ecotoxicity impact obtained using the ReCiPe method was observed in the dechlorination process. This is because IMPACT2002+ has specific characterization factors for aniline emissions, whereas ReCiPe does not have. Overall, ReCiPe generates results similar to those of IMPACT2002+. The results indicate that IMPACT2002+ is a reliable method.

5 Discussion

Life cycle impact assessment results are currently illustrated using a selection of key indicators: respiratory inorganics, global warming, terrestrial ecotoxicity, land occupation, and nonrenewable energy (see Fig. 3). In each scenario, the electron donor production phase was the most important phase (accounting for more than 80% of adverse impacts) in most key categories, except in global warming. The direct methane emissions observed in the methanogenic process also represented dominant contribution to global warming. These results indicate that electron donor concentration is a key to decreasing the environmental impacts. However, sufficient electron donors and nutrients are generally applied in bioremediation to eliminate any limitation of electron donor and to achieve complete biotransformation. The electrons used for the reductive dechlorination of haloorganic compounds in a mixed acidogenic/methanogenic culture were very small (Pavlostathis and Prytula 2000; Tas et al. 2006; Loffler et al. 1999). As mentioned earlier, approximately 99% of electrons amended are used by halorespiring pure cultures (Tas et al. 2006). In addition, Loffler et al. (1999) observed that as much as 70% of electrons are used by halorespiring pure cultures at a high initial chlorinated solvent concentration. If actual electrons for PCA dechlorination were applied, the potential impact in most key categories, except in the terrestrial ecotoxicity, will be reduced to around 99% (Fig. 7). In the terrestrial ecotoxicity, the effect in the glucose + methanol, methanol, lactate, and acetate scenarios will be decreased by approximately 34%, 27%, 80%, and 64%, respectively. Similarly, if electron donor concentration is decreased by 70%, the potential impact in most key categories, except in the

Table 2 Sensitivity of electron donor application

Categories	Acetate	Lactate	Methanol	Glucose + methanol
Variation (%)	−20	−20	−20	−20
Respiratory inorganics (kg PM2.5 eq)	-1.3×10^{-8}	-1.7×10^{-8}	-3.0×10^{-9}	-3.9×10^{-9}
Terrestrial ecotoxicity (kg TEG soil)	-3.5×10^{-4}	-8.2×10^{-4}	-7.3×10^{-5}	-1.0×10^{-4}
Land occupation (m^2org.arable)	-9.2×10^{-8}	-1.5×10^{-5}	-1.8×10^{-8}	-1.9×10^{-6}
Global warming(kg CO_2 eq)	-3.5×10^{-5}	-4.2×10^{-5}	-2.3×10^{-5}	-2.4×10^{-5}
Nonrenewable energy(MJ primary)	-6.9×10^{-4}	-4.9×10^{-4}	-3.7×10^{-4}	-3.4×10^{-4}

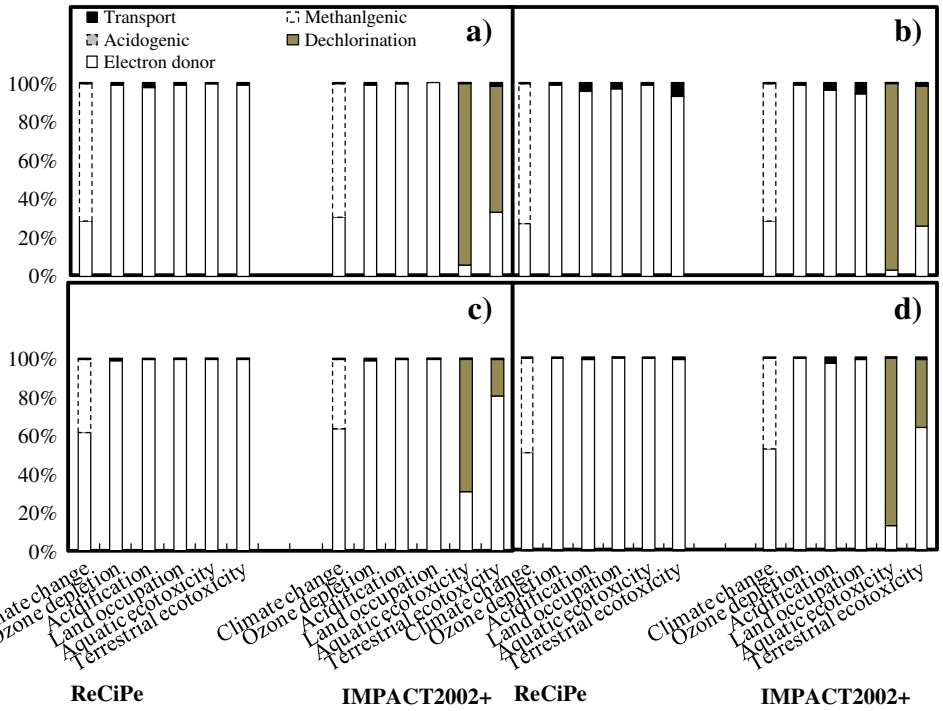

Fig. 6 Contribution of processes to the midpoint score for: **a** methanol+glucose, **b** methanol, **c** lactate. **d** acetate

terrestrial ecotoxicity, will be reduced to around 70% (see Fig. 7). In the terrestrial ecotoxicity, the effect in the glucose + methanol, methanol, lactate, and acetate scenarios will be decreased by approximately 24%, 19%, 56%, and 45%, respectively. It is noteworthy that acidogenic/methogenic processes are relatively fast processes. If only actual electrons for PCA dechlorination were applied, some limitation caused by electron donor may be generated. Accordingly, optimizing the concentration of amended electron donors through laboratory experiments is highly

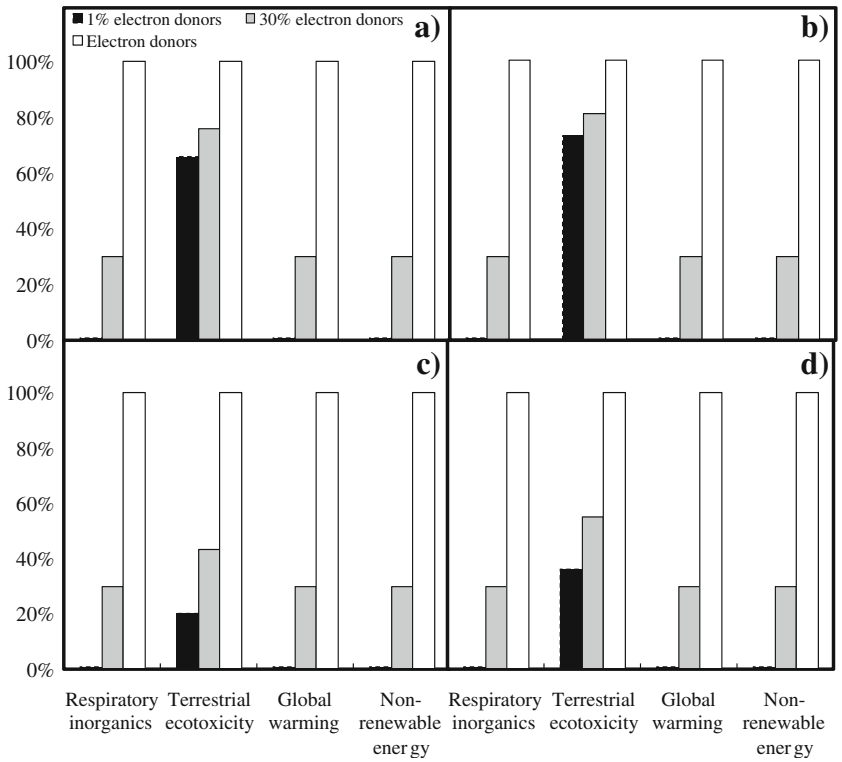

Fig. 7 Relationship between key indicators and electron donor application: **a** methanol + glucose, **b** methanol, **c** lactate, **d** acetate (IMPACT2002+ method)

recommended. Moreover, the reductive dechlorination rate of haloorganic compounds is generally proportional to biomass concentration (Rhee et al. 2001; Pavlostathis and Prytula 2000; Tas 2006), indicating that the population size of dechlorinating microorganisms is crucial to the PCA transformation rate. In addition, Fig. 3 showed that 7.5% of the potential impact on nonrenewable energy decreased with partly changing electron donor (13%) in the methanol to glucose application. By contrast, the potential impact on the respiratory inorganics, terrestrial ecotoxicity, global warming, and land occupation increased by around 31%, 11%, 2%, and 100% with partial change in electron donors in the methanol to glucose application. Thus, if only glucose is used as the electron donor, the overall environmental impact generated from the glucose scenario will be higher than that observed in the methanol scenario. These results indicate that choosing glucose, lactate, and acetate for PCA bioremediation is not a suitable choice from an environmental perspective.

In addition, PCA generally exhibits a trend of decreasing toxicity with declining degree of chlorination (Argese et al. 2001). Argese et al. (2001) reported that no significant difference in ED50 values among CAs was observed. Lo et al. (1990) reported an increase in the neuphrotoxic toxicity of DCA on male Fischer 344 rats in the order 2,3-DCA<2,6-DCA, 3,4-DCA, 2,4-DCA, and <2,5-DCA<3,5-DCA. Accordingly, although PCA biodechlorination can decrease the toxicity of the parent compound, the biodechlorinated product (i.e., DCAs and CAs) remains toxic. These results are consistent with those of the IMPACT2002+ model, which provides a characterization factor for the cancer, noncancer, aquatic ecotoxicity, and terrestrial ecotoxicity potential impact of PCNB and its byproducts. The results calculated using the IMPACT2002+ method show a significant decrease in both carcinogens and noncarcinogens toxicity of DCA and CA compared with their parent compounds. However, amended artificial chemicals exhibited more overall environmental burden, even in the case of electron donor concentration that is decreased by 99%. Accordingly, studying to the use of natural organic carbons to enhance the bioremediation of organic contaminants is highly needed.

6 Conclusions

This study compared the life cycle environmental impact of PCA biodechlorination under acidogenic/methanogenic conditions using alternative electron donors. To add credibility to the study, sensitivity analysis was also conducted. The results are expected to aid in the development of laboratory experimental research and provide useful scientific information for decision makers as they formulate policies regarding the bioremediation of PCA contamination.

The primary findings of the study are summarized as follows.

- In all the scenarios, the potential impacts on the respiratory inorganics, global warming, and nonrenewable energy categories represented dominant contribution.
- In all the scenarios, the emissions from the electron donor production processes played an important role, whereas the potential impact generated from the acidogenic processes were negligible. In addition, the PCA dechlorination process imposed a significant effect on the aquatic and terrestrial ecotoxicity categories because of DCA accumulation. Furthermore, the direct methane emissions observed in the methanogenic process represented dominant contribution to the respiratory organic and global warming.
- The methanol scenario was the most suitable option determined in this research.
- Amended electron donors can cause fewer environmental impacts on carcinogens and noncarcinogens categories. By contrast, they can generate a significant increase in environmental impacts in respiratory inorganics, global warming and nonrenewable energy categories.
- Increasing the population size of dechlorinating microorganisms and optimizing the amended electron donor concentration is highly recommended to reduce adverse environmental impacts.

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